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Stratigraphy and origin of regolith in the East Yornaning catchment, south-western Yilgarn Craton, Western Australia

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Abstract

Using a lithostratigraphic approach, the regolith within the East Yornaning catchment is subdivided into two major units of weathered Precambrian bedrock origin and a further four major units of sedimentary origin. The oldest sedimentary unit is the Westonia Formation, a mainly crudely stratified, light red clayey quartz sand, deposited along valley side-slopes by unconfined sheet-wash during the middle–late Tertiary. Unconformably overlying the Westonia Formation and weathered bedrock with a gradational contact is the Mulline Formation, a mainly dark red, pisolitic, quartz sandy aluminous duricrust. Petrographic and granulometric analyses indicate that the Mulline Formation is a secondary or "overprint" lithofacies, developed within upper sections of the Westonia Formation and weathered bedrock largely as a result of the allogenic addition of fine-grained quartz. Weathered basement and the Mulline and Westonia formations are unconformably overlain by the Gibson Formation, a dominantly light grey, massive, bimodal quartz sand, deposited as aeolian sand sheets during arid phases coeval with high latitude glaciations in the Pleistocene. Completing the sedimentary sequence and underlying most of the landsurface is the Nuendah Formation, a mainly grey, crudely stratified, muddy quartzo-feldspathic sand. The Nuendah Formation ranges in age from the present where it is forming along valley floors and side-slopes by fluvial and colluvial processes, through to the early Quaternary where it fills small palaeovalleys situated beneath the present major valley floors. The sequence of Gibson Formation grey sand overlying Mulline Formation pisolitic duricrust overlying Westonia Formation red clayey sands resembles the uppermost zones of a granitic deep weathering profile. Careful examination of regolith strata on a case by case basis is required for reliable interpretations of regolith genesis.

Introduction

A complex regolith covers much of the Precambrian bedrock along the south-western margin of the Yilgarn Craton in Western Australia (Simpson 1912; Prider 1966; Finkl & Churchward 1973; Anand & Paine 2002). Many aspects of the regolith in this region have been studied in considerable detail, including the development of weathering profiles over different bedrock types (Sadlier & Gilkes 1976; Davy 1979), the alteration of primary minerals at the weathering front (Gilkes & Suddhiprakaran 1979; Anand *et al.* 1985), the mineralogical properties of aluminous and ferruginous duricrusts (Grubb 1966; Anand *et al.* 1991), the near-surface geochemical expression of bedrock mineralization (Davy & El-Ansary 1986), the hydrological characteristics of weathered bedrock aquifers (George 1990), the relationship between regolith, soils and landforms (Mulcahy 1960; McArthur *et al.* 1977), and the nature and origin of surficial Mesozoic and Cenozoic sedimentary strata (Finkl & Fairbridge 1979; Salama 1997). No studies, however, have documented in any great detail the major lithological properties, stratigraphic relationships and origins of all regolith strata within an entire hydrological catchment.

A major advantage of including all strata in a geological study of the regolith is that it provides a basis for the distinction of units produced by the *in situ* chemical weathering of crystalline basement rock from those units produced by sedimentary processes. Owing to close similarities in texture and composition between weathered basement and overlying sediment, and the poor preservation of primary sedimentary and igneous structures, unconformable contacts between the two major regolith types may easily escape detection. Furthermore, as will be demonstrated here, traditional models used to infer regolith type and origin from landform and landscape position are often unsatisfactory, and it is only through a detailed study of regolith strata on a case by case basis that reliable interpretations of regolith genesis can be made.

Using a non-genetic, lithostratigraphic approach (Salvador 1994), the regolith within the East Yornaning catchment is subdivided into six major units, two of which are interpreted to have formed by the *in situ* weathering of Precambrian bedrock (granite and dolerite), and four of which are interpreted to be of sedimentary origin. The latter are correlated with formations formally established by Glassford (1987) for sedimentary regolith in the north-eastern and central Yilgarn Craton. Correlations with other relevant lithostratigraphic schemes are, however, also considered for the sake of completeness. The origins and ages of the regolith units are also discussed. However, formational ages, whether they relate to deposition, weathering or some other form of near-surface alteration, are typically poorly constrained.

Nomenclature

Following Eggleton (2001), the term "regolith" is used here to refer to the entire succession of earth materials overlying fresh bedrock, which in the context of the south-western Yilgarn Craton generally equates to Precambrian granite, gneiss or dolerite (see below). The regolith therefore includes materials of widely different colour, induration, structure, fabric, texture, composition, age and origin.

Some regolith "lithofacies", *i.e.* materials of similar lithological composition, stratigraphic position and presumably also genesis, may be produced by the chemical weathering of Precambrian basement. Other lithofacies may be distinct primary sediment types (that need not be weathered), whereas others still may be produced by alteration processes that overprint weathered bedrock and sediment in a like manner and therefore pass from one regolith type to the other with only a subtle change in lithological properties. A good example of this is ferruginous or aluminous "duricrust", which is an indurated, generally nodular to pisolitic lithofacies rich in secondary iron or aluminium minerals

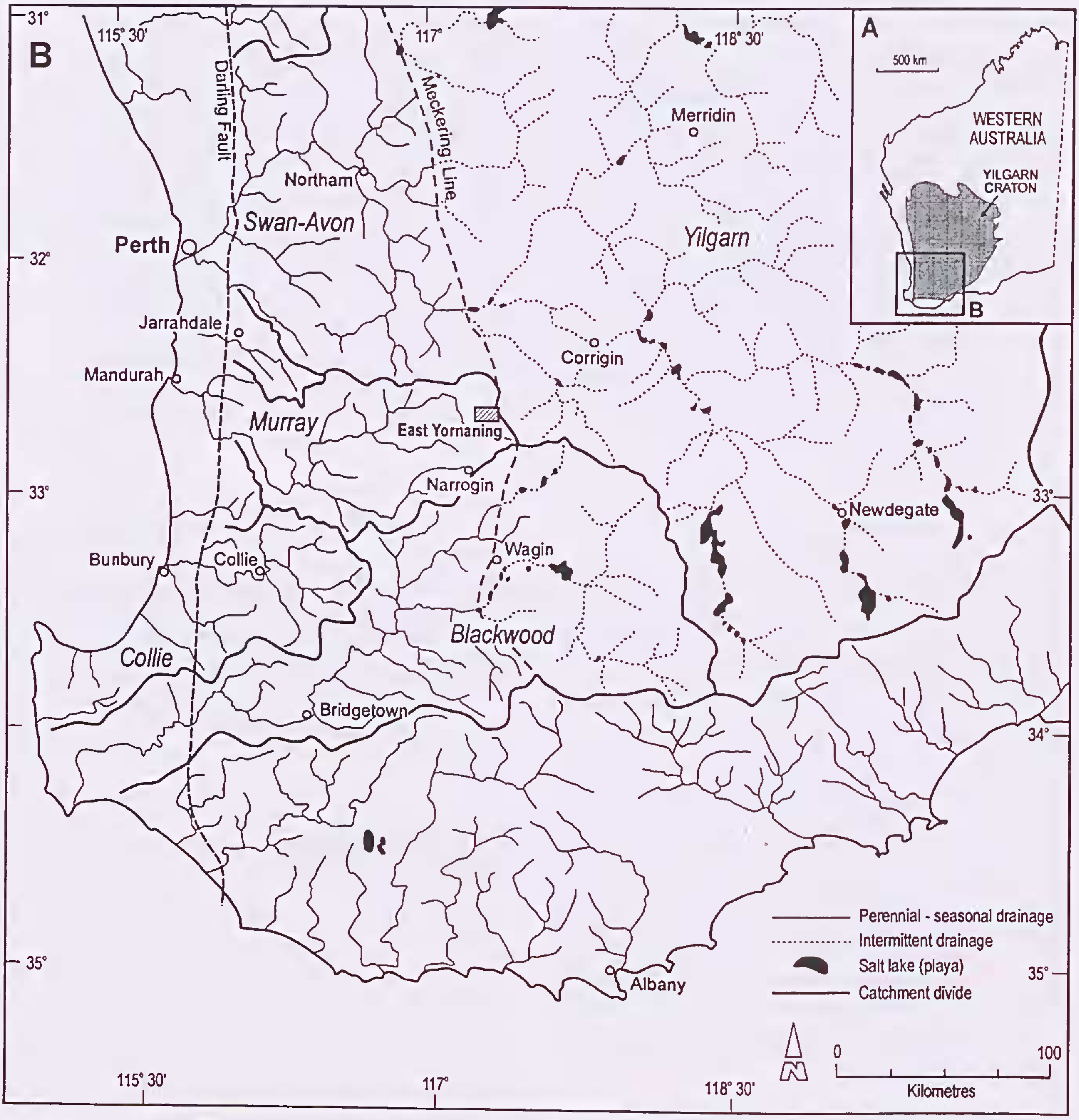


Figure 1. Regional setting of the East Yornaning catchment. A: Location of the south-western Yilgarn Craton within Western Australia. B: Location of the East Yornaning catchment within the south-western Yilgarn Craton. Major drainage basins and eastern limit of incised drainage (Meckering Line) also shown. Modified after Mulcahy (1967) and Beard (1999).

that acts as a protective cap for other less indurated regolith materials at the landsurface. Woolnough (1927), who coined the term duricrust, believed it to be the product of deep weathering under conditions of strongly seasonal rainfall and perfect peneplanation, but it is used here purely as a descriptive term without genetic connotation. Another term, frequently used synonymously with the ferruginous form of duricrust, is "laterite", but I avoid the use of this term owing to numerous conflicting opinions as to its meaning (Terrill 1956; Bourman 1993; Eggleton & Taylor 1999). A similar problem exists with the term "ferricrete", which in South Australia is generally used to describe iron-rich surficial materials regardless of their origin (Milnes *et al.* 1985; Bourman 1993), but in Western Australia is commonly used for detrital sediments that have been impregnated and cemented by iron oxides and oxyhydroxides (Anand 1998; Anand & Paine 2002).

General setting

The East Yornaning catchment comprises an area of about 14 000 ha within the western margin of the wheatbelt, bounded by latitudes 32°39' and 32°46' S and longitudes 117°11' and 117°25' E (Fig 1). The catchment is elongate in an E–W direction and is drained by a fourth-order tributary (*sensu* Strahler 1952) of the Hotham River, in the upper reaches of the Murray drainage basin (Fig 1). Its eastern interfluve is shared with the Swan–Avon drainage basin (Beard 1999) and, more importantly, also forms part of the Meckering Line (Mulcahy 1967). Originally delineated by Jutson (1934), this NNW–SSE trending zone marks the transition from relatively steep-sided, narrow-floored and high-gradient valleys in the west, to much broader and flat-floored valleys locally occupied by chains of salt lakes (playas) to the east (Fig 1).

Most workers (*e.g.* Bettenay & Mulcahy 1972; Mulcahy *et al.* 1972) accepted the view of Woolnough (1918) and Jutson (1934) that the Meckering Line represents the landward (eastward) limit of stream rejuvenation following late Tertiary (?Pliocene) epeirogenic uplift of the Darling Peneplain to form the Darling Plateau, part of the Great Plateau of Western Australia. A very different interpretation by Finkl & Fairbridge (1979) is that the valleys west of the Meckering Line were cut by marginal uplift of the Yilgarn Craton in the Late Jurassic associated with the onset of sea-floor spreading between Australia and Greater India.

Drainage within the East Yornaning catchment is seasonal and follows a dendritic pattern in higher-order streams, which becomes rectangular in lower-order tributaries owing to the increased influence of basement structure (Fig 2). Being very close to the inland limit of incised drainage, the major valleys are still fairly flat-floored and of low gradient (Mortlock type valley form of Bettenay & Mulcahy 1972). The side-slopes of major valleys are gentle (~2.5%) and typically terminate in outcrops of fresh bedrock, or small cuestas of pisolitic duricrust, most of which dip gently to the north and are bounded by low breakaways to the south. Outcrops of pisolitic duricrust also occur as spurs extending down to the valley floors. Although the largest exposures of bedrock are in upland areas (Fig 2), fresh bedrock crops out in almost all landscape positions, including the valley floors, reflecting the highly irregular and unpredictable form of the basal weathering surface (Fig 3A). Elevation within the catchment ranges from ~310 to ~450 m AHD, with the majority of the landsurface lying between the 320 and 370 m contour intervals.

The basement rocks at East Yornaning comprise part of the Western Gneiss Terrane of the Archaean Yilgarn Craton (Myers 1990), and have been mapped by Chin (1986) as plutons of even-grained to seriate to porphyritic, biotite granites and adamellites (Fig 4A). These were emplaced after the last period of regional deformation and metamorphism, and are thus characterised by a lack of gneissic foliation or metamorphic recrystallisation. Also forming a large part of the basement in the catchment are Mesoproterozoic dolerite dykes of the Boyagin dyke swarm (Lewis 1994; Pidgeon & Nemchin 2001). The dolerite dykes are poorly exposed, but in aeromagnetic imagery can be traced for tens of kilometres across the catchment, mostly following a NW trend. In middle to upper landscape positions, the dolerite dykes are locally associated with prominent landsurface and basement highs (Fig 3A). This may be due to the relatively high resistance to weathering of the dolerite dyke itself (Bettenay *et al.* 1980), or more likely to the relatively high resistance to weathering and erosion of the baked margins in the adjoining contact metamorphosed granite (Prider 1948).

A Mediterranean climate, with cool, wet winters and hot dry summers, characterises the region. The average annual rainfall for Narrogin is about 500 mm with most rain (70%) falling during mid-May to October. Annual potential evaporation is about 1 900 mm and exceeds rainfall for 9 months of the year (Bureau of Meteorology, personal communication 1996). Most of the catchment was cleared for agriculture in the 1950s and is now widely affected by secondary salinity.

Methods

Exposures of regolith in the form of breakaways, road cuts, stream banks, drainage ditches, farm dam spoil and three transects of cored boreholes drilled to refusal depth (Fig 2) were used to produce stratigraphic sections and obtain representative samples of all major regolith rock-types (lithofacies) within the catchment. An additional 26 boreholes, drilled by the rotary air-blast method, provided more accurate information on the depth to fresh bedrock, but were not lithologically logged as part of this study. Surface exposures were mapped onto 1:25 000 scale colour aerial photographs, which in conjunction with stereoscopic observation and interpretation of airborne electromagnetic imagery (de Broekert 1996) formed the basis for the construction of a surface geology map (Fig 2).

Epoxy-impregnated thin sections were prepared of most samples to better characterise aspects of fabric, texture and composition. As a further check on mineralogical composition, samples that were thin-sectioned were also air dried, ground and X-rayed from 5–65° 2θ at 1° min^{-1} using Cu Kα radiation. Semi-quantitative estimates of mineral abundance were obtained using the SIROQUANT software package (Taylor & Clapp 1992) and kaolinite crystallinity (order–disorder) was estimated using a peak height ratio and empirical index developed by Hughes & Brown (1979).

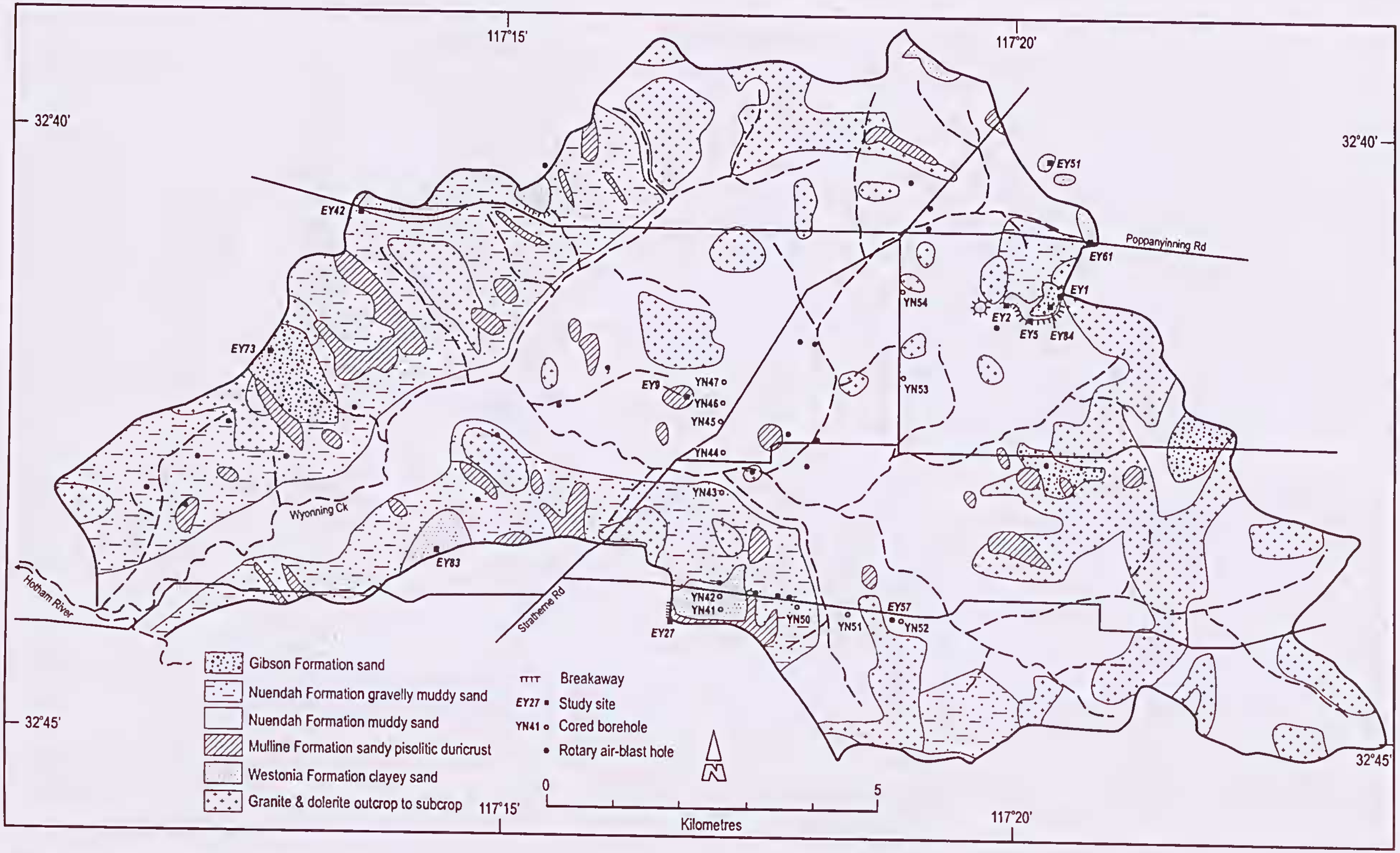


Figure 2. Geology map of the East Yornaning catchment with locations of boreholes and study sites mentioned in text.

In the course of petrographic analysis, attention was paid to differences in the textural and compositional properties of quartz (Folk 1974), this being the only primary mineral present in abundance within all lithofacies. A similar study of the varietal properties of zircon, including sensitive high-resolution ion microprobe (SHRIMP) U–Pb age determinations, is to form the subject of a separate paper.

Grain-size distributions of quartz in representative samples of each lithofacies were obtained by dry sieving at ½ ϕ intervals over the granule to fine sand-size range (4–0.063 mm, or -2–4 ϕ). Sample preparation of loose materials involved dispersion in a dilute solution of Calgon and NaOH using an overhead stirrer, followed by wet sieving through a 45 µm screen. Indurated samples, such as pisolitic duricrust, were first coarse crushed and then repeatedly boiled in concentrated NaOH and/or HCl, depending on the cementing agent. Following dissolution of the cementing minerals, the samples were disaggregated using an ultrasonic probe and then wet sieved as above. Statistical measures of the grain-size distributions (mean, mode, sorting, skewness and kurtosis) were derived by the graphic methods described by Folk (1974). Terminology of overall grain-size distribution (mud, sandy clay, gravelly sand *etc*) is based on textural triangles developed by Folk *et al*. (1970). In this classification, the term "mud" refers to a sediment composed of subequal proportions of clay-sized (<4 µm) and silt-sized (4–63 µm) particles and has no implication of moisture content. Although the textural terminology of Folk *et al*. (1970) was developed for detrital sediments, its application is here extended to some highly weathered bedrock lithofacies which are very similar in texture and mineralogical composition to certain, generally clay-rich, detrital sediments.

Stratigraphy

Weathered Granite

Distribution, geometry & dimensions. Weathered granite forms the bulk of the regolith at East Yornaning and is developed in all landscape positions except where fresh bedrock is exposed or where the Precambrian basement is composed of mafic dykes. It has a highly irregular basal surface, commonly varying greatly in thickness over small lateral distances. Nevertheless, the greatest thicknesses of weathered granite (40–50 m) tend to be concentrated along major valley floors, and along interfluve zones capped by Westonia Formation nodular sandstone or Mulline Formation pisolitic duricrust (Fig 3A).

Lithic characteristics. Based primarily on differences in overall grain-size distribution, mineralogical composition (essentially the degree to which the "weatherable" primary minerals in the parent granite have been altered) and stratigraphic position, weathered granite can be subdivided into the following three lithofacies.

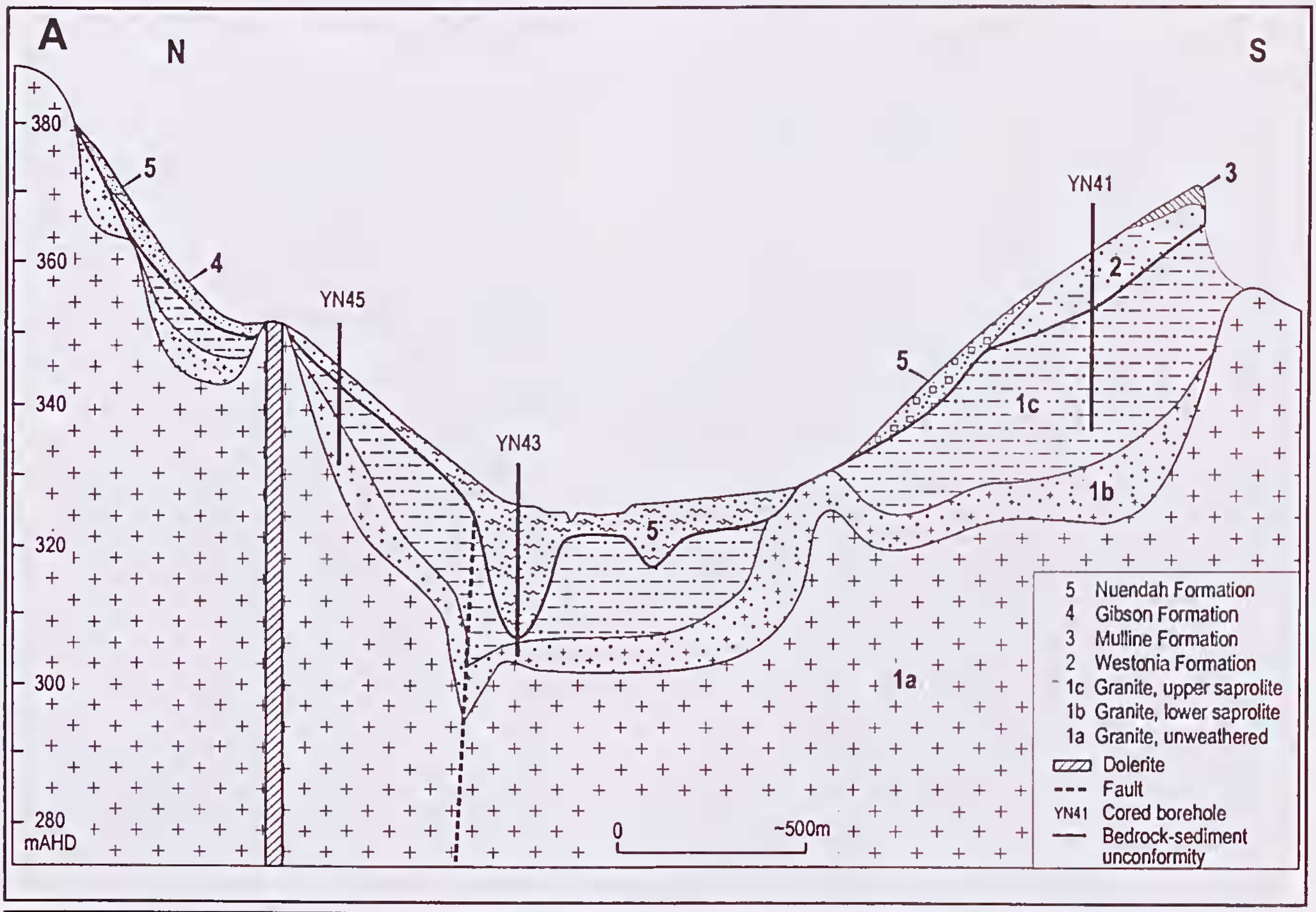
1. Saprock lithofacies. This material is very similar to granite (Table 1) except for minor alteration of the chemically unstable primary minerals (*e.g.* plagioclase, biotite, hornblende, apatite) along grain boundaries, cleavage planes, cracks and other macro- and micro-structural discontinuities.
2. Lower saprolite lithofacies. This typically comprises white to yellow to light red, poorly indurated, matrix supported, coarse sandy clay (Fig 4B). Sand-sized particles are composed of muscovite, variably kaolinized microcline, and quartz, which together form a conspicuous palimpsest or remnant granitic fabric. Kaolinite pseudomorphs of biotite and plagioclase form much of the matrix and exhibit a moderate degree of crystal structure disorder.
3. Upper saprolite lithofacies. This material is typically a white, poorly indurated, coarse quartz sandy kaolinite clay, similarly exhibiting a strong remnant granitic fabric (Fig 4C). Kaolinite pseudomorphs are more prominent than in the lower saprolite facies and exhibit a moderate to low degree of disorder. Framework quartz grains are mostly strongly unimodal, coarse, poorly sorted, mesokurtic and characteristically fine to very fine skewed (Fig 5). The presence of abundant highly spherical quartz grains in the fine to very fine sand-sized sieve fractions is also characteristic (Fig 6A). Petrographic examinations of fresh granite in the catchment indicate that these occur as inclusions within alkali feldspar (Fig 6B,C) and were released from the rock following weathering of the feldspar to kaolinite (Fig 6D). Conversely, the coarse sand-sized quartz grains are all subequant, very angular, and commonly contain holes left by the weathering of inclusions, such as biotite. Polycrystalline quartz, which accounts for about half of the coarse sand-sized grains, typically comprises 3–4 roughly equally-sized crystals with strongly undulose extinction (Fig 7A,B).

A zone of unconsolidated, coarse-grained material with a highly porosity and permeability commonly occurs immediately above fresh granite and gneiss in the south-western Yilgarn Craton ("saprolite grit" aquifer of George 1990). This was not, however, observed at East Yornaning, possibly owing to poor surface exposure and the limited penetration depth of the cored boreholes.

Structure. The weathered granite lithofacies are structureless, except for where cut by dolerite dykes, faults, shear zones or quartz veins.

Stratigraphic relationships. The saprock lithofacies overlies fresh granite with a gradational contact over a vertical interval of <1 m and is overlain by the lower saprolite lithofacies with a gradational contact over a vertical interval of 1–3 m. A similarly gradational contact occurs between the lower and upper saprolite lithofacies. All three contacts are highly irregular and rapidly converge approaching outcrops of fresh granite.

Origin. Remnant granitic fabric, a progressive upward reduction in the proportion of primary minerals, gradational contacts, and the preservation of primary igneous structures, all indicate that the three lithofacies were formed by the weathering of granite. Similar materials have been described elsewhere in the south-western Yilgarn Craton by Gilkes *et al*. (1973) and McCrea *et al*. (1990), which these authors also regard as having been formed by the weathering of granite.



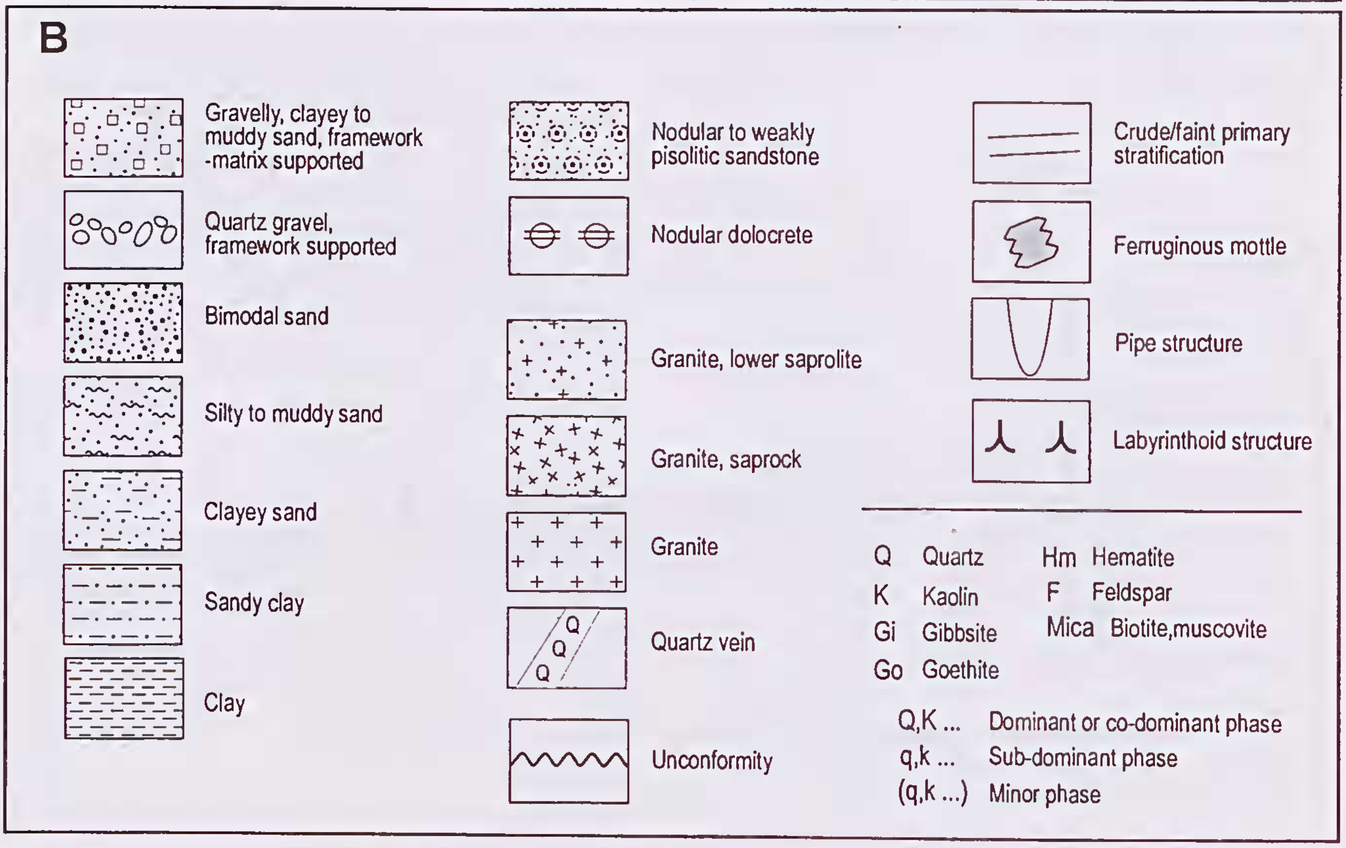


Figure 3. A: Schematic geological section across the East Yornaning catchment. Cored boreholes YN41, YN43 and YN45 positioned with respect to regolith stratigraphy rather than exact geographic location. Depths to fresh and slightly weathered basement (saprock) provided by rotary air-blast holes. B: Legend for stratigraphic sections shown in Figs 3A, 4, 8 and 10.

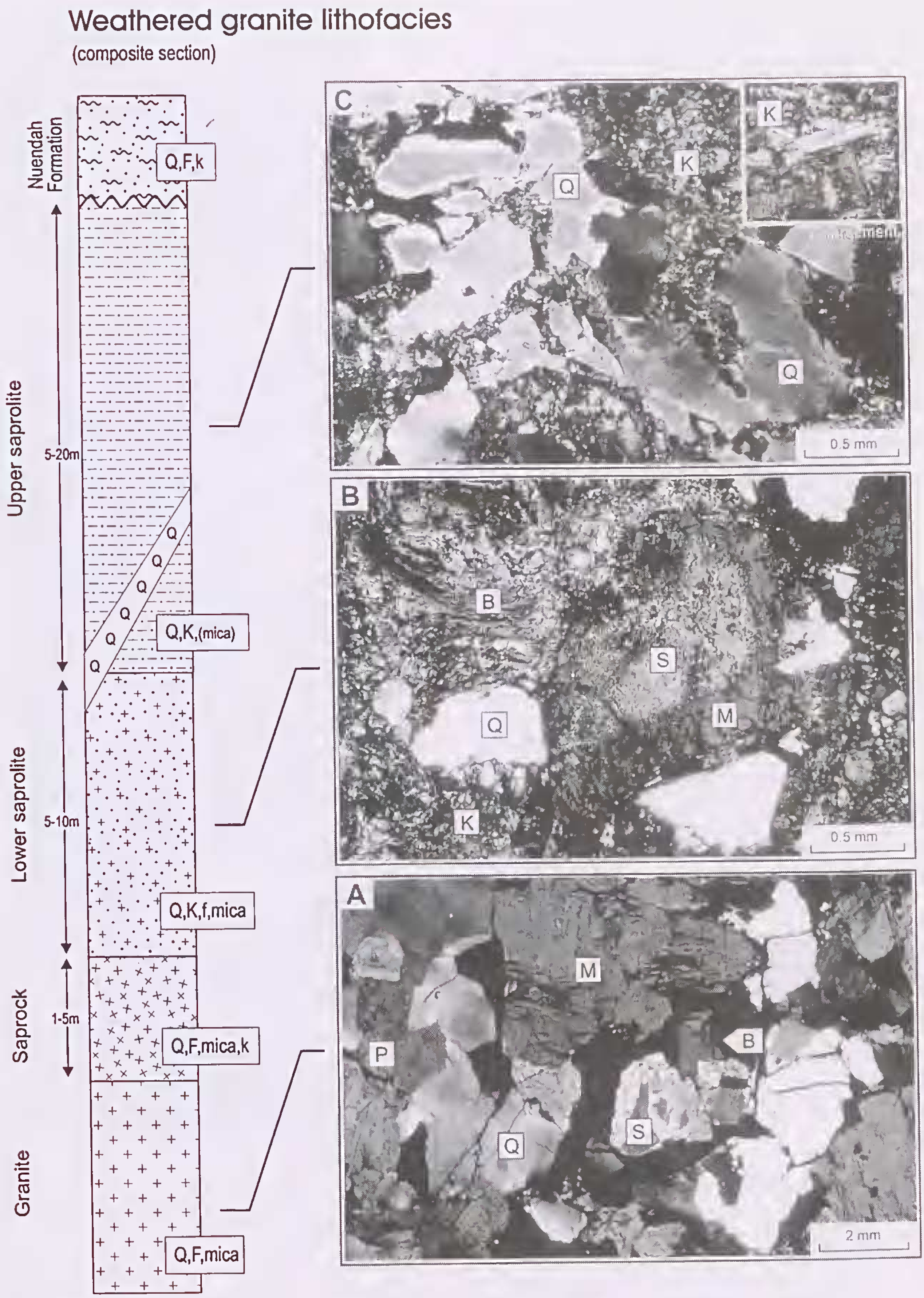


Figure 4. Composite stratigraphic section of weathered granite lithofacies with representative optical photomicrographs. **A:** Fresh granite. **B:** Lower saprolite. **C:** Upper saprolite. Inset in C shows enlarged view of vermiform books of kaolinite, which are optimally developed within the upper saprolite. Dominant minerals are quartz (Q), kaolin (K), biotite (B), microcline (M), plagioclase (P), and sericite (S). A = sample EY48/1, B = sample YN42 20.1 m, C = sample YN41 11.4 m; all cross-polarized light.

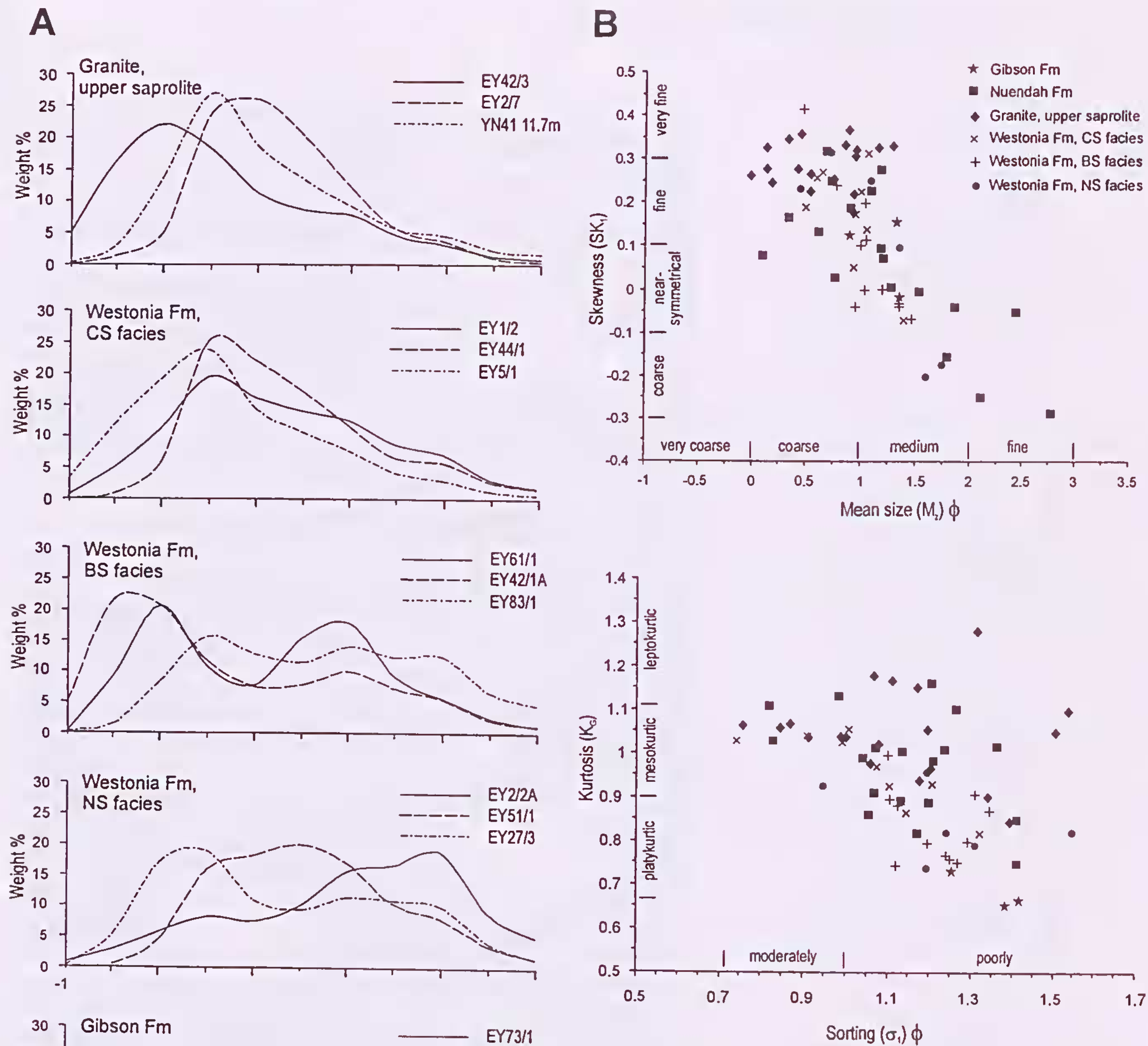


Figure 5. A: Particle size frequency distributions of framework quartz (and feldspar) grains in major regolith lithofacies. B: Bivariate plots of graphic grain size parameters after Folk (1974). For the Westonia Formation: CS = clayey sand to sandstone facies, BS = bimodal sand facies, NS = nodular sandstone facies.

Age. The age of granite weathering at East Yornaning has not been determined. However, a Quaternary age for the (basal) saprock lithofacies seems reasonable given that high rates of weathering are likely to be prevalent within the catchment on account of its humid, temperate climate and appreciable topographic relief. Being further from the zone of primary mineral weathering, the formational age of granitic saprolite is likely to be much older, with a maximum age occurring along interfluve zones where the saprolite commonly lies protected from erosion beneath a cover of Westonia Formation sediment (Fig 3A). Oxygen isotope analysis indicates that granitic saprolite at Collie was formed during the middle–late Tertiary (Bird & Chivas 1989), although a major phase of

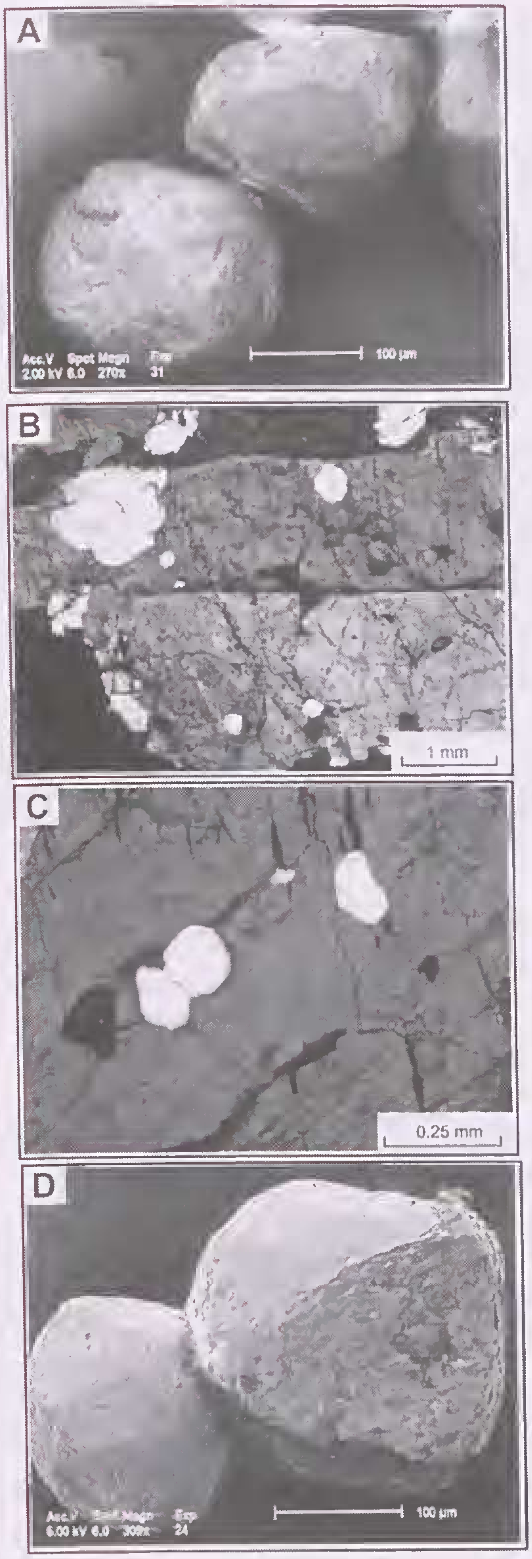


Figure 6. A: Spherical quartz grains in the fine sand-sized fraction of the Westonia Formation. B,C: Inclusions of spherical, fine to very fine sand-sized quartz in alkali feldspar within fresh granite. D: Spherical, fine sand-sized quartz grains in granitic upper saprolite after having been released from alkali feldspar by weathering. Spherical, fine sand-sized quartz grains in the Westonia Formation and other sedimentary units therefore indicative of a granitic provenance. Note that spherical grains appear "rounded", but are actually very angular when viewed under high magnifications. A = sample YN41 5.6 m, B = sample YN11/1, C = sample EY45/1, D = sample YN41 26.1 m. A,D scanning electron photomicrographs; B,C optical photomicrographs using cross-polarized light.

earliest Tertiary weathering has been identified in the eastern Yilgarn Craton based on the palaeomagnetic dating of ferruginous mottles (Pillans, in Anand & Paine 2002).

Weathered Dolerite

Distribution, geometry & dimensions. An aeromagnetic survey of the East Yornaning catchment indicates that weathered dolerite may form up to 15% of the weathered Precambrian basement (World Geoscience Corporation, unpublished data). Thicknesses of up to 40 m are common, although once again the depth of weathering is highly variable with outcrops of fresh dolerite occurring in all landscape positions. Important factors controlling the depth of weathering are likely to include dyke width and associated proximity to granitic baked margins, degree of fracturing, grain-size and mineralogical composition. Most weathered dolerite dykes are near-vertical and about 10–20 m wide (Fig 3A).

Lithic characteristics. Based on limited analyses of samples from East Yornaning and descriptions of weathered dolerite from the Darling Range (Davy 1979; Anand & Gilkes 1984), it appears that the weathering of most primary minerals in dolerite is completed over a very small vertical distance from fresh rock. The saprock and lower saprolite lithofacies are therefore very thin (1–3 m) and will not be discussed further. Upper saprolite samples of dolerite at East Yornaning typically comprise white, poorly indurated to indurated, slightly very fine quartz sandy kaolin clay. Quartz typically makes up about 5% of the rock and occurs as small (50–250 µm), angular, embayed, monocrystalline grains with slightly undulose extinction. Remnant interstitial and granophyric fabric is clearly evident in thin section.

Structure. Apart from the remnants of chilled margins and perhaps xenoliths of granitic country rock, doleritic saprolite lacks primary igneous structures. Secondary structures, in the form of thin closely-spaced ferruginous bands, very similar in appearance to Liesegang rings, are however common.

Stratigraphic relationships. The contact between weathered dolerite and weathered or fresh granite was not observed but is inferred to be vertical to subvertical, planar and sharp.

Origin and age. Remnant igneous fabric and sharp near-vertical contacts with fresh or weathered granite indicate formation by the chemical weathering of dolerite (Sadlier & Gilkes 1976; McCrea *et al.* 1990). The age of dolerite weathering would be similar to that of granite, discussed above.

Westonia Formation

Distribution, geometry & dimensions. The Westonia Formation typically occurs along major interfluve zones as tabular-shaped bodies, which are either flat-lying or gently dipping toward the valley floor (Figs 2, 3A). A maximum thickness of 9.5 m is reached in borehole YN41 (Table 1), although breakaway exposures indicate that thicknesses of 2–4 m are more typical (Table 2). The unit has been extensively truncated by erosion and may once have extended for a greater distance toward the valley floor.

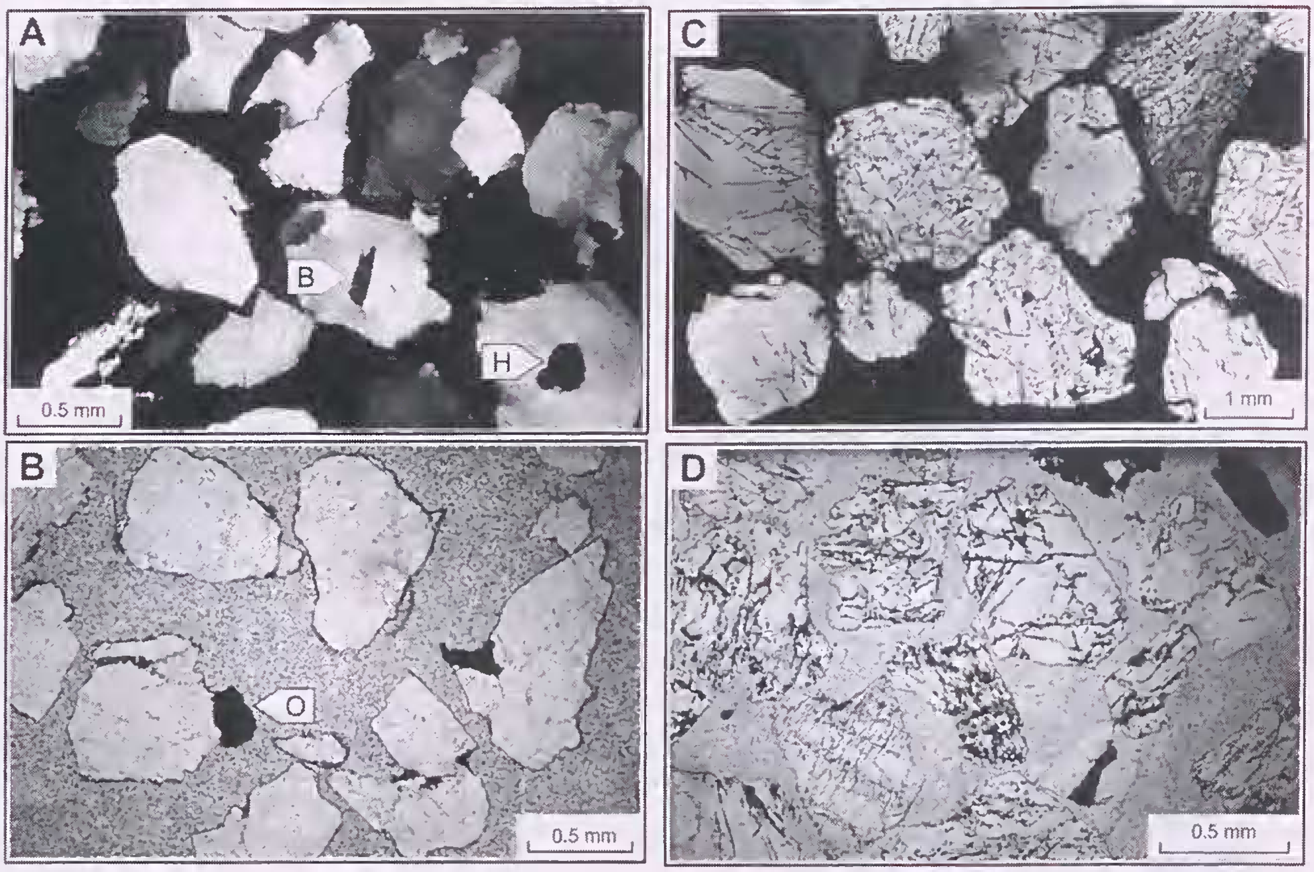


Figure 7. A,B: Optical photomicrographs of coarse sand-sized quartz grains in granitic upper saprolite. Note biotite inclusions (B), holes (H), and attachments of opaque minerals (O). C,D: Optical photomicrographs of coarse sand-sized quartz grains in the Westonia Formation. Note large proportion of fractured, etched, monocrystalline grains without holes, mineral inclusions or attachments, produced by repeated cycles of erosion, transport, deposition and alteration (weathering, pedogenesis) before being incorporated into the Westonia Formation. A,B = sample YN41 26.1 m, C = sample EY61/1, D = sample YN41 7.0 m; A,C cross-polarized light; B,D plane-polarized light.

Lithic characteristics. The Westonia Formation is subdivided into the following three major lithofacies, based primarily on differences in induration, overall grain-size distribution, quartz granulometry and the extent of nodule and pisolith development.

1. Clayey sand lithofacies. This forms the base of the Westonia Formation and is either overlain by the bimodal sand lithofacies (Table 1), or directly by the nodular sandstone lithofacies (Table 2, Fig 8A). It typically comprises yellow to light red, poorly indurated, framework to matrix supported, clayey medium to coarse quartz sand. Where exposed at the landsurface, as in the face of breakaways, the material becomes well indurated forming a clayey sandstone. Matrix (<63 µm) material is dominantly highly disordered kaolinite with lesser gibbsite, goethite and X-ray amorphous minerals. Framework quartz grains are typically unimodal, coarse, poorly sorted, mesokurtic and fine skewed (Fig 5). In contrast to granitic saprolite, the quartz grains are nearly all monocrystalline, strongly etched and free of inclusions (Fig 7C,D). Roundness within the coarser quartz grains is distinctly bimodal, comprising a primary mode of very angular to sub-angular grains and a smaller secondary mode of rounded to well-rounded grains (Fig 9A–C). The rounded quartz grains are severely pitted (Fig 9C) making them more opaque (milky coloured) than the more angular quartz grains when viewed in hand specimen.
2. Bimodal sand lithofacies. This lithofacies is only locally developed and where present crops out at the landsurface or occupies a middle position between the clayey sand and nodular sandstone lithofacies. It comprises yellow, loose to poorly indurated, framework supported, clayey bimodal coarse and fine quartz sand (Fig 5). Except for having thin coats of goethite-impregnated kaolin, the quartz grains have similar external and internal properties to the clayey sand facies. Small quantities of fine sand-sized, spherical to ovate bodies of goethitic kaolin with an internal pelletal or oolitic fabric ("kaolin spherites" of Killigrew & Glassford 1976), are also commonly present. Matrix material is dominantly highly disordered kaolinite with minor goethite and gibbsite.
3. Nodular sandstone lithofacies. This forms the uppermost part of the Westonia Formation at East Yornaning and typically comprises grey to red, well indurated, nodular to incipiently pisolitic, medium quartz sand (Fig 8B). Framework quartz grains are mostly weakly unimodal to polymodal, medium to fine, poorly sorted, platykurtic, and fine to coarse skewed (Fig 5). Rounded quartz once

Table 1

Descriptions of lithology for cored boreholes YN41, YN43 and YN45 at East Yornaning. See Fig 2 for locations.

DEPTH (m)	DESCRIPTION	ROCK UNIT
Bore YN41		
0–0.5	**Sand**; yellow, massive, loose, framework supported, bimodal coarse and fine sand, with framework particles* of poorly sorted, fine skewed quartz and kaolin spherites**; minor rounded quartz in coarser size fractions and trace microcline feldspar in finer size fractions and.	Gibson Formation
0.5–2.8	**Sandy clay**; yellow, massive, poorly indurated, matrix supported, coarse sandy clay, with framework particles of poorly sorted, fine skewed quartz and kaolin spherites in a matrix of moderately disordered kaolinitic clay, quartz, gibbsite and hematite; common yellow to red authigenic ferruginous nodules at base.	Westonia Formation
2.8–5.9	**Clayey sand**; yellow grading to white at base, massive, poorly indurated, framework supported, clayey bimodal coarse and medium sand, with framework particles of poorly sorted, near-symmetrical quartz and kaolin spherites in a matrix of highly disordered kaolinitic clay, quartz, gibbsite and hematite; common reddish brown mottles and yellow, granule-sized, spheroidal to ovate, authigenic ferruginous nodules above 5.5 m.	
5.9–9.1	**Clayey sand**; white, massive, poorly indurated, framework supported, clayey medium sand, with framework particles of moderately sorted, near-symmetrical quartz in a matrix of highly disordered kaolinitic clay, quartz and gibbsite, diffuse light red mottles at top and dark red, indurated mottles and strongly magnetic, authigenic maghemite and hematite nodules at base.	
9.1–10.1	**Sandy clay**; white, massive, poorly indurated, framework to matrix supported, coarse sandy clay, with framework particles of poorly sorted, fine skewed quartz in a matrix of slightly disordered kaolinitic clay and quartz; minor rounded quartz in coarser size fractions.	
10.1–28+	**Granitic (upper) saprolite**; white grading to yellow (goethite stained) at base, massive, poorly indurated, matrix supported, coarse sandy clay, with framework particles of moderately to poorly sorted, very fine skewed quartz in a matrix of disordered kaolinitic clay (disorder increasing with depth) and mica group minerals; quartz grains have remnant granitic fabric and kaolinite occurs a millimetre-sized vermiform books.	Archaean basement
Bore YN43		
0–2.4	**Gravelly clayey sand**; brown grading to grey at base, crudely stratified, poorly indurated, framework supported, granular clayey very coarse sand, with framework particles of moderately to poorly sorted, near-symmetrical to fine skewed quartz, feldspar (fresh) and mica in a matrix of moderately disordered kaolinitic clay and quartz; occasional rounded quartz, detrital ferruginous nodules and angular granitic rock fragments in coarser size fractions.	Nuendah Formation
2.4–17.2	**Interstratified clayey, muddy and silty sand**; grey, massive, poorly indurated, framework supported, interstratified clayey coarse sand, muddy bimodal coarse and fine sand, and silty medium to fine sand. Framework particles typically poorly sorted, near-symmetrical to coarse skewed and composed dominantly of quartz and feldspar, with feldspar decreasing in abundance and freshness with depth; occasional rounded quartz and detrital ferruginous nodules in coarser size fractions.	
17.2–17.6	**Clay**; white, massive, poorly indurated, halloysite and kaolinite clay, common sharp red mottles and authigenic ferruginous nodules.	
17.6–18.4	**Silty sand**; light grey, massive, poorly indurated, framework supported, silty very fine sand, with framework particles of moderately sorted, coarse skewed quartz.	
18.4–19.2	**Gravelly clayey sand**; light grey, massive, poorly indurated, framework supported, granular clayey coarse sand, with framework particles of poorly sorted, fine skewed quartz.	
19.2–23+	**Granitic saprock**; white grading to yellow (goethite stained) at base, massive, poorly indurated, moderately weathered, medium grained, anhedral–equigranular, aphyric, muscovite granite.	Archaean basement
Bore YN45		
1–4.2	**Gravelly muddy sand**; light grey to brown, crudely stratified, poorly indurated, framework supported, fine pebbly muddy coarse sand, with framework particles of poorly sorted, near-symmetrical to fine skewed, granule to fine pebble-sized magnetic ferruginous nodules and sand-sized quartz and feldspar (fresh) in a matrix of moderately disordered kaolinitic clay; occasional rounded quartz in coarser size fractions.	Nuendah Formation
4.2–11.0	**Granitic (upper) saprolite**; white to reddish brown, massive, poorly indurated, matrix supported, very coarse sandy clay; with framework particles of poorly sorted, fine to very fine skewed quartz and mica group minerals in a matrix of slightly disordered kaolinitic clay and goethite; quartz grains have remnant granitic fabric; slightly silicified at top.	Archaean basement
11.0–23+	**Granitic (lower) saprolite**; white to yellow; massive, poorly indurated, matrix supported very coarse sandy clay, with framework particles of poorly sorted, fine skewed quartz, feldspar (weathered) and mica group minerals in a matrix of moderately disordered kaolinitic clay; quartz grains have distinct remnant granitic fabric.	

* Framework particles are >63 mm in size; matrix particles <63 mm in size; ** framework particle types listed in decreasing order of abundance.

Table 2

Descriptions of lithology for breakaway exposure EY2 at East Yornaning. Note that Gibson Formation sand occurs ~50 m back from breakaway face. See Fig 2 for location.

DEPTH (m)	DESCRIPTION	ROCK UNIT
0–0.3	**Sand**; light grey, loose, framework supported, bimodal coarse and fine sand, with framework particles* of poorly sorted, near-symmetrical quartz**; trace microcline feldspar in finer size fractions and trace rounded quartz in coarser size fractions.	Gibson Formation
0.3–0.5	**Nodular clayey sand**; as above, except cemented into large, highly irregular, light red nodules by fine sand- to silt-sized quartz, kaolinitic clay, goethite and hematite.	
0.5–0.8	**Nodular to weakly pisolitic sandstone**; reddish yellow, nodular to weakly pisolitic, indurated to well indurated, framework supported, weakly bimodal medium and coarse sand, with framework particles of poorly sorted, coarse skewed quartz in a matrix of gibbsite, silt-sized quartz, highly disordered kaolinitic clay and goethite; minor rounded quartz in coarser size fractions; numerous voids between nodules and incipient pisoliths.	Westonia Formation
0.8–2.1	**Clayey sandstone**; reddish yellow, crudely horizontally stratified, indurated to well indurated, weakly silica cemented; framework to matrix supported, clayey coarse sand, with framework particles of poorly sorted, near-symmetrical quartz in a matrix of highly disordered kaolinitic clay, gibbsite and goethite; minor rounded quartz in coarser size fractions and scattered angular pebbles of vein quartz at base.	
2.1+	**Granitic (upper) saprolite**; white, massive, poorly indurated, matrix supported, coarse sandy clay, with framework particles of moderately sorted, fine skewed quartz, in a matrix of kaolinitic clay and mica group minerals.	Archaean basement

* Framework particles are >63 mm in size; matrix particles <63 mm in size; ** framework particle types listed in decreasing order of abundance.

again forms a minor but conspicuous part of the coarse to very-coarse sand sized fraction. Matrix material is dominantly silt-sized quartz, gibbsite, goethite, hematite and highly disordered kaolinite.

Structure. The clayey sand to sandstone facies is crudely horizontally stratified, very similar to near-modern deposits of Nuendah Formation muddy sand, which occupy the same valley-side and interfluve landscape positions (Fig 3A). The other facies lack primary sedimentary structures, but commonly contain pipes outlined by hematitic mottles and infilled with similar material to the sediment in which they occur. Similar structures are widespread at the Jarrahdale bauxite deposit and have been interpreted by Grubb (1966) to be infilled cavities left by the decay of ancient plant roots.

Stratigraphic relationships. The Westonia Formation typically unconformably overlies weathered Precambrian granite and dolerite with a sharp contact. Where not exposed at the landsurface, it is typically unconformably overlain by the Gibson Formation with a sharp contact, or the Mulline Formation with a gradational contact over a vertical interval of about 0.2 m.

Correlation. In terms of lithology, stratigraphic position and landscape position, the three lithofacies of the Westonia Formation at East Yornaning correlate most closely with the sandstone to muddy sandstone facies of the Westonia Formation as defined by Glassford (1987). A similarity in terms of lithology, stratigraphic and landscape position also exists with the ?Eocene Kojonup Sandstone (Churchill, in McWhae *et al.* 1958), although this sediment contains plant macrofossils, a basal conglomerate, and is partly feldspathic (Wilde & Backhouse 1977), which is unlike the Westonia Formation at East Yornaning or its type section.

The Quagering Beds of Finkl & Fairbridge (1979) is an angular quartz sand with rounded quartz pebbles which is underlain by Precambrian basement, overlain by "laterite", and distributed as "upland residuals" along the Ravensthorpe Ramp south of Bridgetown. As such, it too may be a lithostratigraphic equivalent of the Westonia Formation.

Origin. Crude primary sedimentary structures, bimodal grain-size distributions and rounded quartz grains all indicate that the Westonia Formation is sedimentary and was not produced by the *in situ* chemical weathering of granite. Furthermore, the Westonia Formation overlies dolerite dykes from which, given the large differences in quartz abundance and grain-size, it cannot have been produced by *in situ* weathering.

Close similarities in terms of landscape position, geometry, structure and overall grain-size distribution between the clayey sand facies of the Westonia Formation and the muddy sand facies of the Nuendah Formation, suggest that the two units share a common origin, albeit widely separated in time. Since the Nuendah Formation ranges to the present and is currently forming along valley sides by a combination of unconfined sheet-wash and downslope creep (see below), it can be inferred that the basal clayey sand facies of the Westonia Formation formed in a similar manner.

The combination of well-developed grain-size bimodality, kaolin spherites and clay-coated quartz grains within the bimodal sand facies of the Westonia Formation is suggestive of an aeolian origin (Folk 1968; Warren 1972; Glassford & Semeniuk 1995). Such an interpretation is also consistent with the lithofacies' patchy distribution and valley side position, with all aeolian cross-stratification having been destroyed by bioturbation (root growth, faunal burrowing *etc*) and the clayey matrix having been produced by the post-

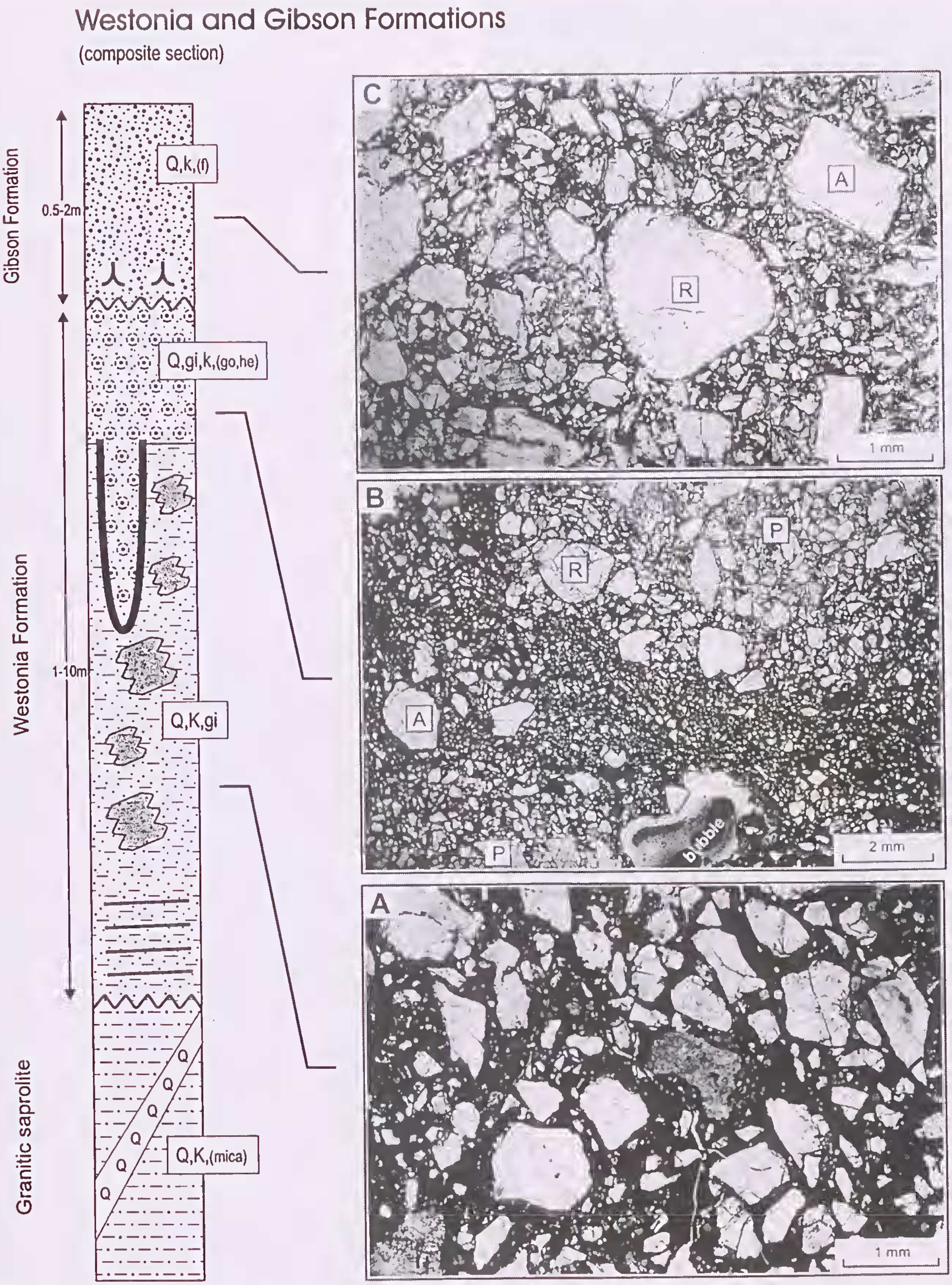


Figure 8. Composite stratigraphic section of the Westonia and Gibson formations with representative optical photomicrographs. A: Westonia Formation clayey sandstone. B: Westonia Formation nodular sandstone. C: Gibson Formation grey bimodal sand. Note incipient pisolith nuclei (P) in Westonia Formation nodular sandstone, and combination of well rounded to rounded (R) and very angular to subangular (A) quartz grains in Westonia Formation nodular sandstone and Gibson Formation grey sand. A = sample EY2/1C, B = sample EY2/2, C = sample EY65/1; all plane-polarized light.

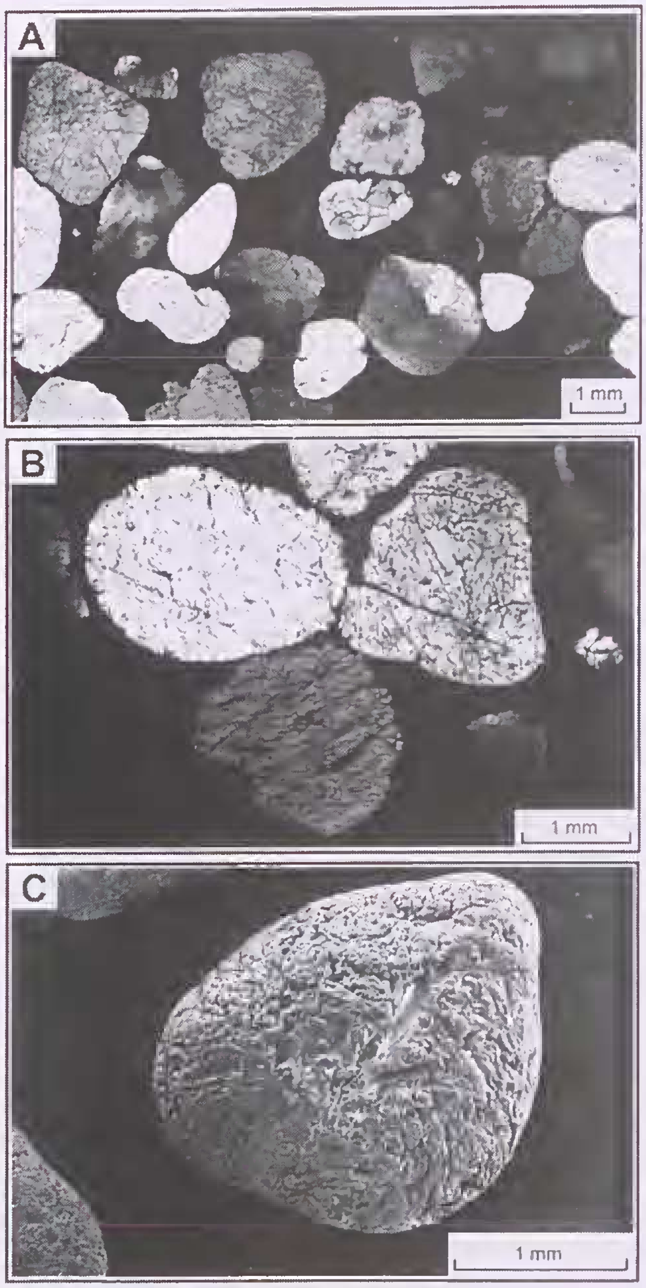


Figure 9. A–C: Rounded, very coarse sand-sized quartz grains in the Westonia Formation. The rounded quartz grains were probably ultimately sourced from an ancient texturally mature (?fluviatile) sediment. A,B = sample EY61/1 optical photomicrographs cross-polarized light. C = sample EY61/1 scanning electron photomicrograph.

depositional infiltration of fine particles, possibly derived from aeolian dust.

Post-depositional infiltration of fine material seems to have played a much more prominent role in development of the nodular sandstone facies of the Westonia Formation. In this case, large quantities of very fine to fine sand-sized quartz appear to have penetrated the uppermost part of the bimodal sand facies, or more commonly the clayey sand to sandstone facies (Table 2). Accompanying or following the influx of fine material, there has been a segregation of coarser and finer quartz grains to form nodules, which, with further reorganization become incipiently pisolitic. Good examples of this progression are shown in Fig 8B and Plate 1A.

Comparisons between thin sections and grain-size distributions show that the degree to which nodules are developed is directly proportional to the amount of fine sand added by infiltration. Thus, samples with a quartz grain-size distribution similar to that of the original clayey sand sediment, such as EY27/3 in Fig 5A, are only weakly nodular. Samples, such as EY2/2A, in which a fine mode and negative skew have been created by the addition of abundant fines, are on the other hand strongly nodular. Confinement of this process to the uppermost metre or so of the Westonia Formation only and the absence of broken rounded quartz grains (Fig 8B) indicates that the "addition of fines" is not simply a result of *in situ* quartz particle breakage associated with weathering or pedogenesis.

Provenance. Possible sources of the fines in the nodular sandstone facies of the Westonia Formation include (1) aeolian dust, as in the case of the bimodal sand facies of the Westonia Formation, (2) the overlying Gibson Formation, which also comprises a large proportion of fine to very fine sand-sized quartz (Fig 8C), and (3) some other overlying sediment, all vestige of which was removed during creation of the unconformity that separates the Westonia and Gibson formations.

Weathered granite is likely to have been the dominant source-rock for the other two Westonia Formation lithofacies, although the reworking of a pre-existing texturally mature (?fluviatile) sedimentary cover is indicated by the presence of small quantities of well-rounded quartz grains. The preponderance of monocrystalline quartz grains, both rounded and angular, with numerous embayments and etch features, variously filled with matrix material (Fig 7C,D), further suggests that both source-rock types had been subjected to pedogenesis (Cleary & Conolly 1972; Eswaran *et al.* 1975). An abrupt change to much fresher quartz grains in granitic saprolite immediately below the Westonia Formation (Fig 7A,B) indicates that pedogenic alteration of the quartz grains was not primarily achieved after deposition of the Westonia Formation.

Age. There is no evidence that can be used to directly date deposition of the Westonia Formation. However, since the unit is extensively eroded and unconformably overlain by the Gibson Formation, interpreted to be Pleistocene, a middle–late Tertiary age seems likely. This concurs with a probable Eocene age for the Kojanup Sandstone (Wilde & Backhouse 1977) and Quagering Beds (Finkl & Fairbridge 1979).

Mulline Formation

Distribution, geometry & dimensions. As with the Westonia Formation, the Mulline Formation comprises only a small proportion of the regolith at East Yornaning. It forms small, dissected plateaux ("lateritic gravel plains") along interfluve zones and small rounded hills in various landscape positions. Less commonly, it occurs as narrow discontinuous spurs that extend for several hundred metres from the interfluve zones toward the valley floors (Fig 2). The consistent

NW trend of these suggests a close genetic relationship with dolerite dykes or the baked margins in granite alongside the dolerite dykes. The small hills capped by Mulline Formation are, on the other hand, mostly composed of variably weathered granite, whereas the interfluve plateaux are mostly composed of the Westonia Formation. Although rarely fully exposed, it appears that the Mulline Formation has an undulating sheet-like geometry with an average thickness of about one metre.

Lithic characteristics. The Mulline Formation is typically a reddish brown, indurated to well indurated, strongly nodular to pisolitic, quartz sandy aluminous duricrust (Plate 1B). Pisoliths range up to about 1.5 cm in diameter and comprise nuclei of framework- to matrix-supported fine to coarse quartz sand, enveloped by laminae of framework-supported fine to very fine quartz sand. Contacts between laminae are commonly disconformable suggesting multiple phases of growth by accretion. The inter-pisolith domain typically comprises pisolith fragments and quartz sand thickly coated by gibbsite, which also commonly occurs as ooids. Matrix material of the pisolith nuclei, their surrounding laminae and the inter-pisolith domain is fine-grained gibbsite, quartz, X-ray amorphous minerals, highly disordered kaolinite, hematite, maghemite and boehmite, in approximately that order of decreasing abundance.

Two less common, but highly genetically significant, variations occur with respect to the composition of the pisolith nuclei. The first relates to Mulline Formation duricrust overlying dolerite, wherein the pisolith nuclei tend to be very iron-rich and contain only a few small highly corroded quartz grains. The second relates to where Mulline Formation duricrust directly overlies weathered granite, wherein the pisolith nuclei exhibit a well-developed remnant granitic fabric in which the remnants of quartz–feldspar–mica domains can be recognised.

Differentiation of the three types of Mulline Formation is generally difficult to achieve in the field, hence separate lithofacies have not been established. Nevertheless, there is a tendency for those pisoliths with remnant granitic nuclei to be loosely packed, large and irregularly shaped (more nodular than pisolitic). Pisoliths with highly ferruginous nuclei situated over dolerite tend to be equally large and poorly formed, but in this instance much more dense, magnetic and dark red.

Structure. The Mulline Formation is typically massive, but sporadically contains cavities and vertical pipes that are empty to partly filled with detritus. As with the nodular sandstone facies of the Westonia Formation, the pipes are probably related to the growth and decay of ancient plant roots.

Stratigraphic relationships. The basal surface of the Mulline Formation is poorly exposed, but is inferred to be gradational with weathered granite, weathered dolerite and thick sequences of Westonia Formation.

Correlation. Except for a lack of kaolin spherites and a greater abundance of secondary aluminium minerals (principally gibbsite), the Mulline Formation at East Yornaning is very similar to the Mulline Formation at its type section (Glassford 1987). It also correlates in terms of lithology and stratigraphic position with most other pisolitic iron- and aluminium-rich duricrusts in the south-western Yilgarn Craton (*e.g.* Mulcahy 1967; Finkl & Churchward 1973; Hickman *et al.* 1992), although these may not all have been formed by the same process or at the same time.

Origin. Mulline Formation pisolitic duricrust is essentially a secondary or "overprint" lithofacies that cuts across primary lithological contacts. In some cases it has developed entirely within sediment (Westonia Formation), whereas in others it has developed within weathered Precambrian granite or dolerite. The nature of the original or "host" material is most clearly reflected by the composition of the pisolith nuclei, rich in quartz sand rich for Westonia Formation, hematite-rich for weathered dolerite, and gibbsite-rich (with remnant granitic fabric) for weathered granite. In the case of weathered granite, it is necessary for the host material to have been either saprock or lower saprolite in order to account for the presence of gibbsite pseudomorphs after feldspar within the pisolith nuclei.

The alteration (pedogenetic, diagenetic, weathering) processes responsible for ferruginous or aluminous pisolitic duricrust formation are complex, varied and beyond the scope of this paper (*e.g.* Nahon 1991; Anand & Paine 2002). An essential ingredient in the formation of Mulline Formation pisolitic duricrust, however, appears to have been the addition of fine to very fine quartz sand (Glassford & Semeniuk 1995), in the same manner inferred to be responsible for development of the nodular sandstone facies of the Westonia Formation. Indeed, the nodular sandstone facies of the Westonia Formation can be regarded as an immature form of, or transition to, the sand-rich facies of the Mulline Formation (compare Plates 1A and 1B). Incipiently developed pisoliths within some samples of otherwise strongly pisolitic sand-rich Mulline Formation, provide further evidence of this paragenetic sequence.

Another condition necessary for the development of Mulline Formation pisolitic duricrust appears to have been a fairly impermeable substrate, preventing excessive downward movement and dilution of the added fine sand grains (Glassford & Semeniuk 1995). This requirement would have been readily satisfied in the case of outcropping weathered basement and thin successions of Westonia Formation overlying weathered basement, but would not have been achieved where the Westonia Formation was thick. Thus, depending on its thickness, the Westonia Formation may either have been completely converted to Mulline Formation, or incompletely transformed to Mulline Formation over a small depth beneath the ancient landsurface (Table 2).

Age. The age of Mulline Formation pisolitic duricrust has not been directly determined. However, a late Tertiary (?Miocene) age seems probable based on an inferred middle to late Tertiary age for the Westonia Formation, which it overprints, and an inferred Quaternary age for the Nuendah Formation, into which the Mulline Formation has been reworked. Using palaeomagnetic evidence, a late Tertiary age for "lateritization" has also been determined by Schmidt & Embleton (1976) for outcrops of Paleozoic and Mesozoic sediments in the northern Perth Basin (data reinterpreted by Pillans, in Anand & Paine 2002).

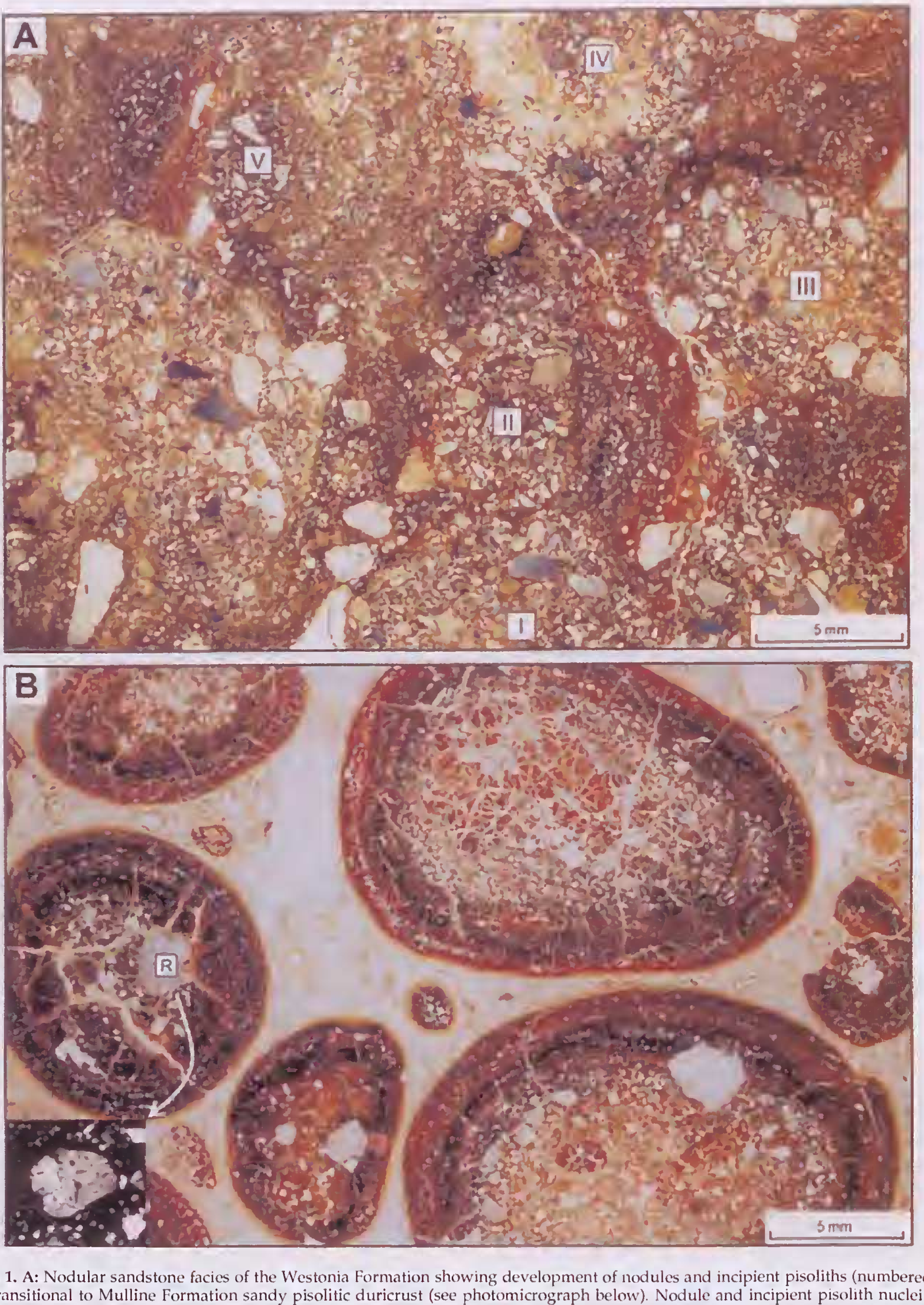


Plate 1. A: Nodular sandstone facies of the Westonia Formation showing development of nodules and incipient pisoliths (numbered I–V), transitional to Mulline Formation sandy pisolitic duricrust (see photomicrograph below). Nodule and incipient pisolith nuclei are composed of coarser quartz grains typical of underlying clayey sand facies of the Westonia Formation, whereas the intervening areas are composed of allogenic finer quartz grains arranged into poorly- to well-developed curvilinear laminae around the nuclei. **B:** Mulline Formation sandy pisolitic duricrust developed within the upper part of the Westonia Formation. Inset shows enlarged and rotated view of a corroded well-rounded quartz grain (R) in one of the pisolith nuclei. A = sample EY2/2A, B = sample EY 9/1. A,B plane polarised light, inset in B cross-polarised light.

Gibson Formation

Distribution, geometry & dimensions. At East Yornaning, the Gibson Formation occurs as small sheets and pods situated in middle to upper slope positions (Fig 2). A marked increase in abundance of the Gibson Formation east of the Meckering Line (Brewer & Bettenay 1973; Glassford 1987), where the climate becomes drier and there has been less fluvial reworking of surficial material, suggests that the sheets of Gibson Formation at East Yornaning were once much more extensive. Limited borehole intersections and sand pit exposures (Tables 1, 2) indicate that the Gibson Formation has a thickness of 0.5–2 m.

Lithic characteristics. The following two lithofacies of the Gibson Formation can be recognised, based primarily on differences in colour.

1. Grey bimodal sand lithofacies. This facies forms the vast bulk of the Gibson Formation at East Yornaning and is composed of white to light grey, loose to poorly indurated, framework supported, poorly sorted, bimodal very coarse and fine quartz sand (Fig 5). Trace amounts of fresh microcline feldspar can be detected in X-ray diffractograms and thin sections of the medium to fine sand-sized sieve fractions. Framework quartz grains are virtually all monocrystalline, highly etched and very angular to angular, though a small proportion of coarse, well rounded to rounded quartz is also present (Fig 8C). Where overlying granitic saprolite, or some other impermeable material, basal sections of Gibson Formation grey sand contain large, irregularly-shaped, authigenic ferruginous nodules (Table 2), or less commonly a ~0.5 m thick zone cemented by kaolin, gibbsite, goethite and silt-sized quartz (Fig 8).
2. Yellow bimodal sand facies. This facies has a very restricted spatial distribution at East Yornaning, having only been found in the top of borehole YN41 (Table 1). The yellow sand facies of the Gibson Formation is very similar in composition and texture to the grey bimodal sand facies, except that it contains a high abundance of kaolin spherites (~10% in YN41) and has framework quartz grains with thin coats of yellow, goethite-impregnated, kaolinitic clay. The yellow bimodal sand facies of the Gibson Formation can be distinguished from the bimodal sand facies of the Westonia Formation, which is also yellow, on the basis of stratigraphic position and by the presence of trace quantities of fresh feldspar and a larger amount of kaolin spherites.

Structure. Except for authigenic ferruginous nodules, and labyrinthoid structures developed within the basal cemented zone of the grey sand lithofacies (Fig 8), the Gibson Formation is massive.

Stratigraphic relationships. Gibson Formation bimodal sand unconformably overlies the Westonia Formation and variably weathered Precambrian granite and dolerite with a sharp contact (Tables 1, 2). It also unconformably overlies Mulline Formation pisolitic duricrust, but in this case the contact is highly irregular owing to the infilling of cavities with the upper part of the duricrust. Where not exposed at the land surface, the Gibson Formation is unconformably overlain by the Nuendah Formation. An interfingering contact between the Gibson and Nuendah formations is, however, locally present in he central and north-eastern parts of the Yilgarn Craton (Glassford 1987; Glassford & Semeniuk 1995), indicating that the two formations are at least in part temporally equivalent. The presence of an interfingering contact could not be confirmed at East Yornaning due to the lack of suitably positioned boreholes and exposures.

Correlation. Both grey and yellow bimodal sand lithofacies of the Gibson Formation at East Yornaning correlate in terms of geometry, lithology and stratigraphic position with the sand sheet faces of the Gibson Formation in the central and north-eastern Yilgarn Craton (Glassford 1987). A major difference, however, is that the Gibson Formation at East Yornaning is dominantly grey, whereas the Gibson Formation in central and eastern parts of the Yilgarn Craton is dominantly yellow or reddish yellow (Glassford 1987).

Yellow and grey sands with or without coarse sand-to pebble-sized rounded quartz particles are also widely distributed in upland positions along the south-western margin of the Yilgarn Craton (Mulcahy 1960; Mulcahy *et al.* 1972; Finkl & Fairbridge 1979; Bettenay *et al.* 1980; Asumadu *et al.* 1991). In the Darling Range, these sands occupy shallow troughs along major interfluve zones (Goonaping valley form of Bettenay & Mulcahy 1972) and are locally cemented to form a thin "duricrust" (Bettenay *et al.* 1980; Asumadu *et al.* 1991). In both of these respects, this sediment is similar to the Gibson Formation at East Yornaning.

Origin. Basal contacts with a variety of regolith strata, including weathered dolerite dykes, and the presence of a small but distinct quantity of well rounded quartz grains, indicate that the Gibson Formation is sedimentary, and not derived from the *in situ* weathering of Precambrian crystalline basement. Well-developed bimodal grain-size distributions, the presence of kaolin spherites in the yellow sand facies, and a widespread distribution throughout all landscape positions, including the interfluve zones between major drainage basins, further indicate that the Gibson Formation is likely to be aeolian (Glassford & Semeniuk 1995).

The gradation between yellow sand in eastern (drier) areas and grey sand in western (wetter) areas indicates that the grey sand was formed from the yellow sand by the degradation of kaolin spherites and removal of goethitic clay coatings from quartz grains as a consequence of increased rainfall and water throughflow. Assisting in the removal of grain coatings and bleaching of the yellow quartz sand is likely to have been the complexing and mobilization of iron by organic exudates (Hingston 1963; Enright 1978).

Basal cementation of the grey sand facies of the Gibson Formation probably resulted from the downward translocation of silt-clay sized material derived from the degradation of kaolin spherites and the removal of grain coatings from originally yellow sand, as noted above. Additional silt-clay sized particles would have been derived from matrix material deposited along with the framework grains or thereafter, such as from aeolian dust.

Provenance. Trace quantities of fresh microcline feldspar within the Gibson Formation indicate that it was partly derived from exposures of fresh granite, although outcrops of granitic saprolite and the Westonia and Mulline formations are also likely to have been important sources. Aeolian dust, infiltrated into the bimodal sand during or after its deposition, is likely to have been sourced from outside of the drainage basin.

Age. On the basis of its inferred aeolian mode of deposition and uppermost stratigraphic position, the Gibson Formation is likely to have been deposited during arid phases coeval with high latitude glaciations during the Pleistocene (Glassford & Semeniuk 1990, 1995). Bleaching and fluvial reworking of the originally mainly yellow quartz sand is likely to have been accomplished during the Holocene, or interglacial phases during the Pleistocene when the climate would have been relatively humid and a relatively thick vegetation cover would have been supported.

Nuendah Formation

Distribution, geometry & dimensions. The Nuendah Formation forms most of the landsurface at East Yornaning (Fig 2) and comprises the bulk of the sedimentary regolith volume. It occupies narrow palaeovalleys cut into weathered basement beneath the modern valley floors and extends up the valley sides as irregular sheets that wedge out against outcrops of fresh granite, or less commonly, outcrops of the Westonia and Mulline formations (Fig 3A). A thickness of about 20 m for the Nuendah Formation appears to be typical where it fills palaeovalleys, decreasing to an average of about 2 m where it mantles the valley sides.

Lithic characteristics. The Nuendah Formation is very lithologically heterogeneous, but can be broadly subdivided into the following two major lithofacies based on differences in overall grain-size distribution and mineralogical composition.

1. Muddy sand lithofacies. This facies dominates the valley floors throughout the catchment, and also the valley sides in the upper (eastern) part of the catchment where outcrops of granite are particularly widespread. Typically, it comprises light grey, poorly indurated, framework supported, muddy to clayey, medium to coarse sand (Fig 10B,C). Framework grains are weakly unimodal to polymodal, poorly sorted, mesokurtic to platykurtic, coarse to fine skewed (Fig 5), and composed of angular mono- and polycrystalline quartz, granitic rock fragments, and microcline and plagioclase feldspar (Fig 10B,C). Where filling palaeovalleys, there is an overall decrease in the abundance of feldspar and granitic rock fragments with depth. Matrix material typically comprises silt-sized quartz and feldspar, and moderately disordered kaolinite.
2. Gravelly muddy sand lithofacies. This facies dominates interfluve zones and upper valley slopes in the lower (western) part of the catchment, where outcrops of Mulline Formation pisolitic duricrust and Westonia Formation nodular sandstone are most common (Fig 2). It interfingers downslope with the muddy sand facies, and typically comprises grey to brown, poorly indurated, framework supported, gravelly muddy sand (Fig 10A). Gravel particles range from granule to coarse pebble in size and are composed of feldspar, granitic rock fragments, and brown ferruginous nodules and pisoliths with chipped and polished external surfaces. Matrix muddy sand is of similar texture and composition to the muddy sand facies, described above.

Structure. The muddy sand facies is crudely horizontally stratified along valley sides and normally-graded in ephemeral stream channels. Interbedding of the two Nuendah Formation lithofacies is widespread in lower slope and valley floor positions.

Stratigraphic relationships. In valley floor and side positions, the Nuendah Formation typically unconformably overlies the upper saprolite facies of weathered granite with a sharp contact. However, where filling palaeovalleys, it unconformably overlies the saprock facies of weathered granite with a sharp contact marked by a thin angular quartz gravel lag (Table 1; Fig 10). Less commonly, the Nuendah Formation unconformably overlies the Gibson Formation with a sharp contact. Lithostratigraphic investigations of regolith in the central and north-eastern Yilgarn Craton indicate that the Nuendah Formation also interfingers with the Gibson Formation (Glassford 1987; Glassford & Semeniuk 1995), although this could not be confirmed at East Yornaning owing to a lack of suitably positioned boreholes or surface exposures.

Correlation. In terms of lithology and stratigraphic position, the Nuendah Formation at East Yornaning correlates with the clayey sand facies of the Nuendah Formation in the north-eastern Yilgarn Craton (Glassford 1987). In the north-eastern Yilgarn Craton, however, this facies of the Nuendah Formation is typically confined to the base of breakaways, whereas at East Yornaning it occurs in most landscape positions. The more widespread distribution of the Nuendah Formation at East Yornaning probably relates to increased fluvial dissection attendant upon a much greater local relief and higher rainfall.

The Quairading Sandstone of Salama (1997) correlates with the Nuendah Formation at East Yornaning in that it too is largely a clayey quartzo-feldspathic sand that infills bedrock-bounded palaeovalleys developed beneath major modern valley floors. The Nuendah Formation is unlikely, however, to correlate with other quartz sandy palaeovalley fills in the region that are overlain by a thick unit of clay (Waterhouse *et al.* 1994; De Silva *et al.* 2000). Palynological evidence suggests that these valley fills are of Eocene age, which is considerably older than the Nuendah Formation (see below) and more similar in age to the Westonia Formation.

Origin. On valley sides the Nuendah Formation has been, and continues to be, principally deposited by unconfined sheet-wash following heavy rains and to all lesser extent by continuous down-slope creep. In valley-side gullies and along the major valley floors the Nuendah Formation is principally deposited within ephemeral fluvial channels and associated flood plains. Palaeovalleys filled with Nuendah Formation beneath the present valley floors may reflect phases of stream rejuvenation arising from tectonic uplift or changes in climate. In view of the catchment's proximity to the western margin of the Great Plateau and Darling Fault, the former seems more likely.

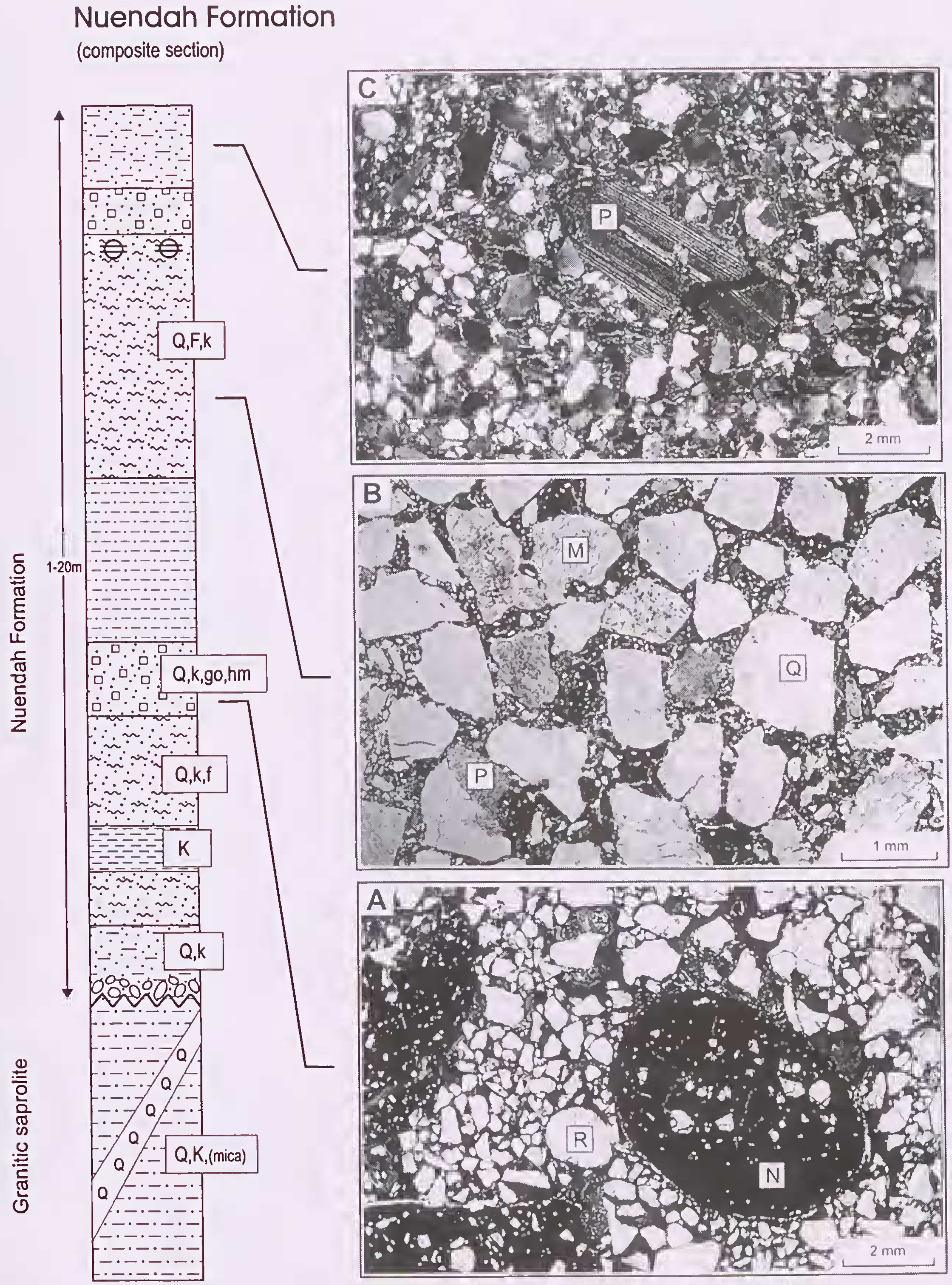


Figure 10. Composite stratigraphic section of Nuendah Formation lithofacies with representative optical photomicrographs. A: Gravelly muddy sand lithofacies. Note rounded quartz grains (R) and ferruginous nodules (N). B: Muddy sand lithofacies. C: Clayey sand. Dominant minerals are quartz (Q), microcline (M), and plagioclase (P). A,B = sample YN43 12.6 m, B = sample EY57/1, C = sample YN43 2.0 m. A cross-polarized light; B,C plane-polarized light.

Provenance. Granitic rock fragments and fresh feldspar within the muddy sand and gravelly muddy sand facies indicate major contributions from fresh granite, with Mulline Formation pisolitic duricrust also contributing significantly to the gravelly muddy sand facies. A decrease in feldspar and granitic rock fragments with depth within the palaeovalleys may simply reflect increased post-depositional weathering with time. Alternatively, it may reflect the progressive stripping of weathered granite (from upper saprolite to saprock) associated with tectonic uplift and incision of the palaeovalleys. The Gibson Formation is also likely to have been an important source for the Nuendah Formation, particularly after Pleistocene arid phases when Gibson Formation sand-sheets would have been more widespread.

Age. The landsurface component of the Nuendah Formation is largely of latest Quaternary (Holocene) age, having been deposited under present conditions of fairly high rainfall and seasonal drainage. The maximum age of the Nuendah Formation is more difficult to establish. However, an early Quaternary age for the base of the Nuendah Formation seems likely on the basis of having interfingering contacts with the Gibson Formation (interpreted as Pleistocene), and that it fills narrow palaeovalleys cut within broader valleys probably formed by epeirogenic uplift of the Great Plateau in the late Tertiary (?Pliocene; Jutson 1934; Bettenay & Mulcahy 1972).

Discussion

Using a non-genetic lithostratigraphic approach, the regolith cover at East Yornaning has been subdivided into six major units, (1) weathered granite (mainly white quartz sandy kaolinitic clay with remnant granitic fabric), (2) weathered dolerite (mainly white slightly quartz sandy kaolinitic clay with remnant interstitial and granophyric fabric), (3) Westonia Formation (mainly light red clayey quartz sand becoming nodular and incipiently pisolitic in uppermost sections), (4) Mulline Formation (mainly red pisolitic sandy aluminous duricrust), (5) Gibson Formation (mainly light grey bimodal quartz sand), and (6) Nuendah Formation (mainly white muddy quartzo-feldspathic sand). Apart from providing a stratigraphic framework for future geological investigations of regolith within the south-western Yilgarn Craton, the results of this study have a number of important implications.

In the absence of clear evidence of transport (cross-stratification, peat beds, basal conglomerate, truncated igneous structures, rounded quartz pebbles *etc*), it may be very difficult to distinguish detrital sediments from weathered crystalline basement. This is because regolith sedimentary strata are typically massive, chemically mature (contain only secondary or ultrastable primary minerals) and texturally immature (have a clay-rich matrix with angular and poorly sorted framework grains), which is very similar to weathered crystalline basement rock. A potential consequence of this similarity is for the sedimentary component of regolith to be underestimated.

The sequence of Gibson Formation sand overlying Mulline Formation pisolitic duricrust overlying Westonia clayey sand, which characterises the interfluve zones at East Yornaning, can readily be mistaken for the sequence of zones produced by the *in situ* chemical weathering of Precambrian granite (Gilkes *et al.* 1973; Sadlier & Gilkes 1976). This error appears to have been made by McArthur *et al.* (1977) in their mapping of the regolith in the East Yornaning and broader Murray River catchments.

Given that the sequence of regolith strata (including pisolitic duricrust) situated along interfluve zones at East Yornaning is largely of sedimentary origin, it seems highly unlikely that a plain underlain by a "laterite" profile formed by the *in situ* weathering of Precambrian basement ("Old Plateau" of Jutson 1934) extended throughout the region, and that the present system of valleys were carved from it. Conceptual models of regolith–landscape development, based on the variable stripping of a regionally contiguous duricrust-capped weathering mantle (Woolnough 1918; Jutson 1934; Mulcahy 1959; Finkl & Churchward 1973; McArthur *et al.* 1977; Mabbutt 1980) are therefore not supported, at least within the East Yornaning area.

As demonstrated by the distribution of the Nuendah Formation, water-laid sediments can be deposited along gently inclined valley side-slopes as well as valley floors. There is therefore no *a priori* need to invoke landscape inversion (*e.g.* Pain & Ollier 1995) to account for ancient fluvial sediments, such as the basal clayey sand facies of the Westonia Formation, that currently occupy upper landscape positions.

The regolith at East Yornaning is polygenetic, containing lithofacies or lithofacies components formed by a variety of processes (*e.g.* alluvial and aeolian deposition, *in situ* chemical weathering, additions and translocation of fines, bleaching of yellow sands by organic acids) that have operated at different times, principally under the influence of climatic and tectonic controls. The sedimentary regolith lithofacies are also largely polycyclic, having been recycled at least in part from pre-existing sedimentary strata. The rounded coarse sand-sized quartz grains at East Yornaning, for example, are likely to have undergone many episodes of erosion, transport, deposition and pedogenesis before being deposited in their present locations.

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